

Low Cost, High Efficiency, Ultra-Low NO_x ARICE Solution Using HCCI Combustion

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Abstract

This report describes the activities related to siting and installation of the multi-cylinder engine for homogeneous charge compression ignition (HCCI) engine operation as part of the Advanced Reciprocating Internal Combustion Engine (ARICE) program. Site selection involved locating a site that was appropriate for engine operation related to the project goals. A key part of the site selection was the choice of the engine generator set. The criteria used for selection of the site and engine generator set are discussed in relation to satisfying the goals of this project. This report describes the work on this task as part of the larger ARICE HCCI engine development project.

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Figure 2 – Design system breakdown for the HCCI conversion of the 3406 Engine.

Figure 3 – Test engine installed on LLNL Site.

Figure 4 – Gas and air supply installation to engine site.

Table Captions

Table 1 – Summary of important performance specifications for base engine, a natural gas 3406 Generator Set operating on Natural gas [1,2].

1. Introduction

This report summarizes the activities related to task 2.4 in the contract statement of work related to the siting and installation of the multi-cylinder. As stated in the contract, completion of this task involves the following components:

- Acquire (not included in PIER budget) a multi-cylinder engine/generator with the engine having order 2 Liter per cylinder displacement. The Caterpillar 3406 (6 cylinder, 14.6L) engine with a spark-ignited natural gas head has been selected as the best candidate for this engine.
- Acquire the necessary materials for engine installation.
- Select a site for the engine installation and enter into the appropriate agreements with the site owner.
- Install the engine at the selected site. The installation shall include:
 - Basic hardware installation
 - Connecting to natural gas fuel supply
 - Connecting to cooling water system
 - Connecting exhaust ventilation
- Operate the engine in its stock spark-ignited (SI) configuration.
- Prepare the Draft Siting and Installation Report. This document shall be submitted to the Commission Contract Manager for review at least 15 working days prior to the 1st Critical Project Review. This document shall be one of the main topics for discussion at the Critical Project Review. This document shall include, but not be limited to information on the completion of the multi-cylinder engine installation and operation in the SI mode.
- Participate in the 1st Critical Project Review.
- Modify this draft document in accordance with comments received during the Critical Project Review. The final version of this document shall be submitted to the Commission Contract Manager within 10 working days after the Critical Project Review. The Commission Contract Manager shall send written notification of approval to the Contractor within 2 working days after receipt. Key elements from this document shall be included in the Final Report for this project.

2. Engine Acquisition

An engine-generator set was acquired through the grace of the Caterpillar Engine Company. Caterpillar provided a natural gas fueled G3406 genset in support of long-term HCCI R&D at LLNL. The engine is ideally suited for conversion to HCCI operation for the purposes of developing the ARICE EPAG system. The engine was delivered by Caterpillar to the LLNL site on May 1, 2003.

Table 1 below shows the performance parameters for the G3401 Engine in spark ignition modes as reported in Caterpillar literature [1,2]. Figure 1 shows the engine in the Caterpillar Facility, prior to delivery to LLNL. This engine was selected as an

appropriate engine for the conversion to HCCI mode based upon the a variety of criteria. The selection of this specific engine was done after a great deal of consultation with Dr. Scott Fiveland of Caterpillar, technical lead of HCCI research activities at Caterpillar, Dr. Joel Hiltner of Hiltner Combustion Systems, an expert in engine systems for power generation, and Prof. Robert Dibble of UC Berkeley, a leading combustion research and longtime LLNL partner on HCCI research, including this project. This genset has many features that are appropriate for the HCCI ARICE EPAG application. The target power output for our HCCI application is 200 kW, and the G3406 genset selected here nominally operates at 190 kW in continuous operation, and up to 240 kW in standby mode. Diesel 3406 engines with identical displacement engines gensets can operate up to 350 kW of power output. Based on previous experience and performance estimates, the conclusion is that sufficient margin exists to be able to achieve the target 200 kW power output.

Table 1 – Summary of important performance specifications for base engine, a natural gas 3406 Generator Set operating on Natural gas [1,2].

Performance Parameters	
Power rating (Continuous Duty)	190 kW
Displacement	14.6 Liters
Bore	137 mm
Stroke	164 mm
Compression Ratio	10.3:1
Fuel Consumption @ 100% Load	64 N-m ³ /hr
Engine efficiency @ 100% Load	29.5 %
NOx emission	19.7 g/bhp-hr
CO	1 g/bhp-hr
HC (Total)	4.2 g/bhp-hr
HC (Non-methane)	0.63 g/bhp-hr
Aspiration	Turbocharged-Aftercooled
Package Dimensions	
Length	4.0 m
Width	1.4 m
Height	2.1 m
Mass	4318 kg

This engine is appropriate for the distributed generation and backup power markets, often considered to be the 50 kW to 10 MW range of operation. The industrial package engine gensets, as supplied by companies such as Caterpillar, Cummins, or Waukesha in the US, typically range from 100 kW-3 MW for a single engine-generator set unit. The G3406 selected is at the lower end of this range, which for research and development purposes gives many advantages. The 200 kW size class has lower fuel supply and energy dissipation requirements relative to the larger scale machines, so resources are significantly less taxed. Fuel supply is a key issue because a larger genset might require access to higher capacity gas supply, which might result in significant time and expense to access. The G3406 is of a scale that fuel supply can be handled with typical readily available industrial supply systems.

The dissipation system for a 200 kW class engine for very typical and commonly available load dissipation systems, i.e. a resistive load bank. Modifications, maintenance, and repair require significantly lower effort. The basic size of the engine is an advantage relative to larger frame machines, as disassembly can be handled with a typical light duty shop hoist. In addition, the 3406 engine benefits from being a widely used engine frame for diesel truck engines. Thus, stock parts and aftermarket parts are widely available from engine parts suppliers at significantly lower cost than would be for the substantially less common larger frame engines.

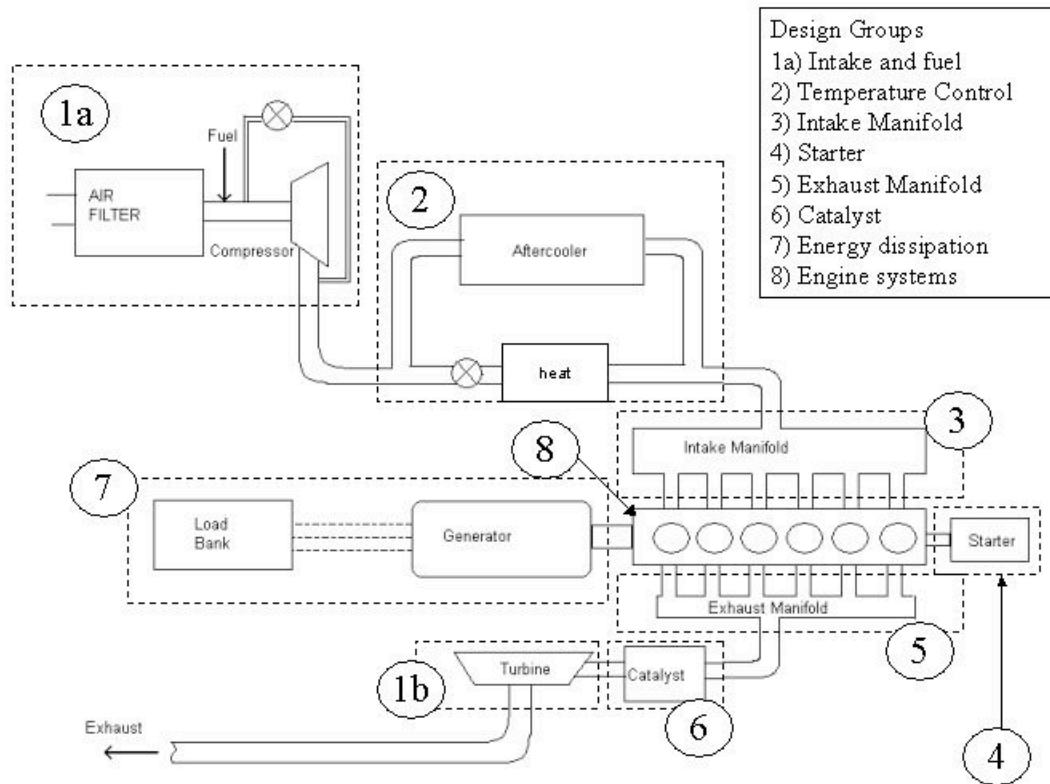


Figure 1- Caterpillar 3401 Genset before delivery to LLNL.

In regard to HCCI engine operation, larger displacement per cylinder engines are actually better suited to operation in HCCI mode, due to lower heat transfer and typically higher surface to volume ratio. Thus the results from this HCCI 3406 engine can be readily applied to larger displacement engines. Even neglecting the potential to scale this engine to higher power output, the 200 kW class is a significant potential market in itself for industrial power generation, power and combined heat and power applications for hotels and commercial establishments, backup power and other applications. The natural gas spark-ignited version of the 3406 has a combustion chamber nearly identical to the Diesel version of this engine. Thus, the engine is designed to withstand Diesel peak pressure loads; pressure loads significantly greater what would be required if the engine were designed to withstand loads required for a spark ignited natural gas engine operation. This is of great benefit for conversion to HCCI operation because the peak pressures are more typical of Diesel operation than of spark ignition operation.

3. Materials Acquisition and Site Selection

After identifying the engine, a layout of the engine system in HCCI operation was developed. Figure 2 shows this layout with detail of the various design groups that need to be addressed for the operating design. The site selection was conducted to accommodate the specific needs identified in this system layout, as well as the package dimensions specified in Table 1. For basic engine setup, the site needs to accommodate the package dimensions and mass, have ready access to sufficient supply of natural gas, and have accommodations for removing the exhaust gas. It is also necessary to consider the impact of the work on other ongoing projects in the area, as the work calls for 1000 hours of running in later tasks of the project.



**Figure 2 – Design system breakdown
for the HCCI conversion of the 3406 Engine.**

An issue unique to this project is the starter system. The starter will be used in this system to “motor” the engine, or established sustained rotation of the engine prior to generation of power by combustion. Because a conventional electric starter can be operated in sustained rotation for less than 30 seconds, it is deemed inadequate for the needs of this project. For the purposes this project, especially in investigating early startup strategies, it is desirable to be able to have sustained rotation for up to several minutes. Alternatives are an electric motor, or an air starter. An AC induction electric motor can effectively start and sustain rotation of the engine. For this engine, it would be necessary to have at least 30 hp for startup. The motor would need to be clutched to be disengaged once power is generated, and would need to have appropriate power electronics to prevent reverse current flow through the electrical system. This electric motor system is estimated to cost \$15K-20K for the hardware and additional cost for installation. The electric motor system would also need to be designed and certified for use on this engine, possibly adding additional cost. An air starter system uses a high capacity air line or a large pressurized air reservoir to drive a air turbine. Air start systems are commercially available for the 3401 engine family with a cost of \$2-3K for the hardware. The air starter system self contained with an internal clutch that automatically disengages when power generation neutrally balances the friction. Thus the air starter was selected as the best choice

and site selection must be able to accommodate an air starter through a high capacity air system or a large air reservoir tank.

Selecting the best site for installation of the engine involves balancing the several factors involved in successful testing. Several sites were considered, a variety of location at LLNL, as well as offsite locations including a facility at UC Berkeley. The selection of the LLNL site was chosen because of the resources available to best support the development and testing under this contract. Siting the engine at LLNL provides the best access to technician support, including access to engine mechanics at LLNL's motor shop. A variety of locations at LLNL with features appropriate for this work were explored. Two sites in particular were considered because of access to a low conductivity water cooling circuit with a cooling tower, a large capacity compressed air system, and a high volume flow natural gas supply. These sites also had heavy duty concrete pads suitable for mounting the engine and necessary access for exhaust. One of the sites was initially selected and preliminary scoping work was performed. This site was chosen because it was more separated from other research projects. But an unforeseen circumstance made this site ineligible soon after the preliminary scoping work was completed; the site was unexpectedly designated by the Department of Energy for demolition. Thus, the site selection reverted to the alternate site, and scoping work began there. This site is on a semi-enclosed pad located adjacent to a building containing a variety of research projects. Some accommodations were necessary to ensure minimum impact on other research projects in the building, such exhaust noise mitigation with a high attenuation muffler and sheet metal screening adjacent to the engine.

4. Engine Installation

Work began on site preparation in anticipation of the arrival of the engine. A collaborative agreement was established with Caterpillar Engine company. Caterpillar agreed to provide LLNL with an genset and engineering guidance on development of the engine. Caterpillar's benefit from this agreement is support on modeling HCCI combustion and multicylinder HCCI control system development. Again, delivery of the engine to the LLNL site occurred May 1, 2003.

Prior to the arrival of the engine site preparations began at LLNL. A senior mechanical engineering technician was involved in coordinating all of the site preparation process. The major resources that needed to be brought to the site were natural gas, high pressure air, and low conductivity water (LCW). The exhaust system also needed to be installed. Fortunately, a natural gas supply with significant excess capacity (9 psig, 2 inch diameter line) was located very near the site. Also located nearby was a high capacity compressed air supply (90 psig, 2 inch diameter line). The pressurized air supply is sufficient for continuous operation of an air start system.

Figures 3 and 4 show the systems installed for engine operation. The natural gas was tapped upstream of the building regulator to have natural gas available at the highest pressure. Compressed air was tapped inside the building from the high capacity supply. In addition LCW lines were extended onto the pad to be available for the engine. The high attenuation muffler was installed in the exhaust line for sound abatement. These modifications involved changes to building systems and utilities, and as such had to be largely handled by LLNL plant engineering in coordination with the project technician. Note that the right-hand-side wall shown in figure 3 corresponds to the left hand side wall in figure 4.

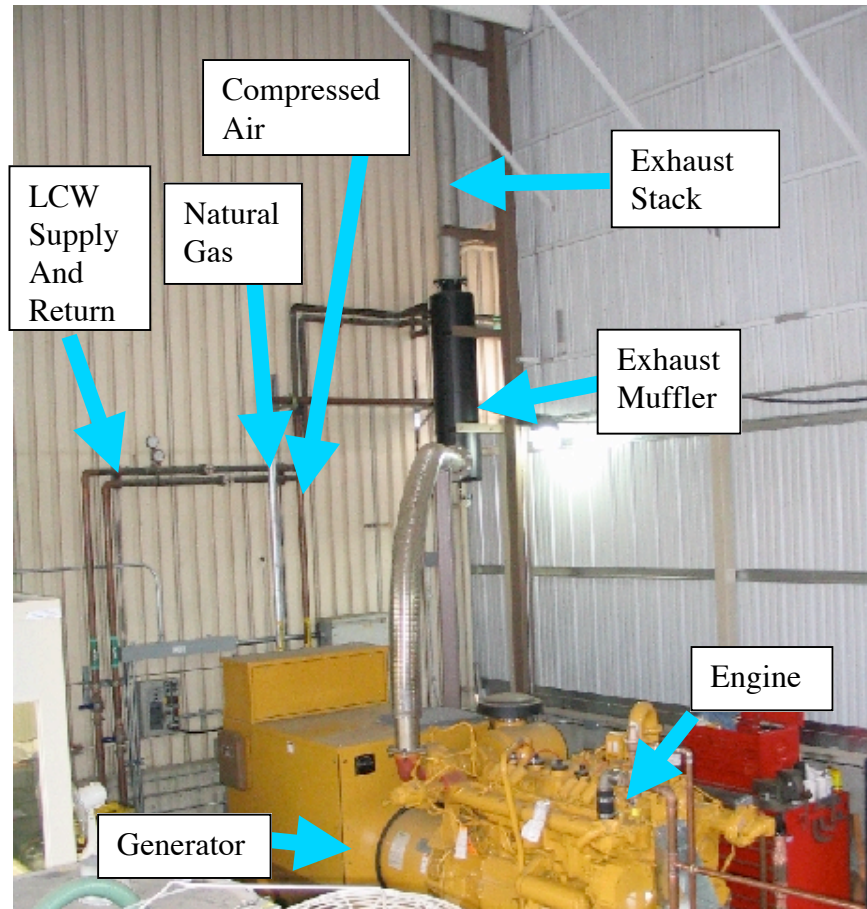


Figure 3 – Test engine installed on LLNL Site.

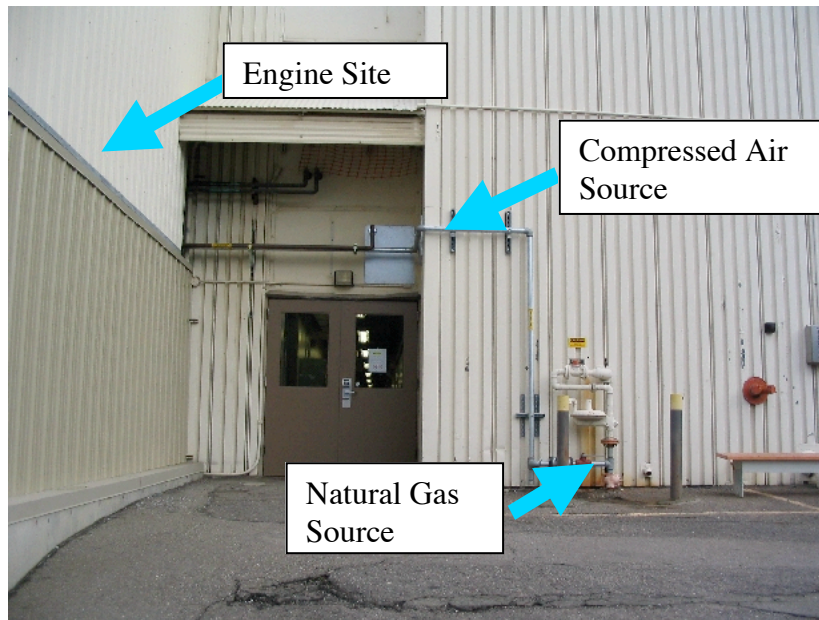


Figure 4 – Gas and air supply installation to engine site.

5. Engine Operation

The infrastructural systems for installing the engine were mostly handled prior to the arrival of the engine (gas, exhaust). Once the engine arrived on May 1, it was moved into place by LLNL riggers, then secured to the concrete pad. The gas line was extended to the engine fuel intake, and the engine exhaust was connected by flexible stainless steel pipe to the exhaust stack. The engine was delivered fitted with a radiator type cooling system, used for initial firing. A test firing of the engine in spark-ignited mode was conducted in late May 2003 to verify all systems were properly functioning prior to making modifications to the engine for HCCI operation. The engine was operated for a total of approximately one hour with several starts and stops. Overall, all engine systems area operate satisfactorily.

6. Reporting

The Critical Project Review was completed at the Energy Commission on December 12, 2003. This report is the final Deliverable for Task 2.4.

7. Conclusions

Siting, installation, and initial firing of the generator set for the ARICE HCCI project has been completed. The engine, a Caterpillar 3406, was chosen as an engine that is appropriate for operation of a natural gas HCCI engine to meet the ARICE targets.

Caterpillar Engine Company has graciously provided an engine generator set for use in this project. A great deal of infrastructure is required to set up a quality facility to for conducting the development work towards the ARICE engine. The design layout, planning, and implementation lays the groundwork for achieving the goals of other tasks in this project.

8. References

1. Caterpillar Engine Company, "Gas Generator Set," LEHE143-02 (03-02), 2001.
2. Caterpillar Engine Company, "G3406 TA: Gas Engine Technical Data," DM5440-00, June 2001.

9. Glossary

ARICE – Advanced Reciprocating Internal Combustion Engine

EGR - Exhaust Gas Recirculation

EPAG – Environmentally Preferred Advance Generation

HCCI - Homogeneous Charge Compression Ignition

HCS - Hiltner Combustion Systems, LLC

LLNL - Lawrence Livermore National Laboratory

UCB - University of California, Berkeley

3401 - Caterpillar 1-cylinder engine model 3401

3406 - Caterpillar 6-cylinder engine model 3406